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THE RELATIONSHIP BETWEEN POLAR CAP RIOMETER ABSORPTION AND SOLAR PARTICLES

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April, 1977

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A detailed investigation of the approximate square-root relationship between riometer absorption and solar proton fluxes has been carried out. The relationship is shown to be valid for night as well as day conditions, with differences in the constants. The atmospheric chemistry basis for the differences in the constants is discussed.

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FOREWORD

The analysis reported herein was carried out under Contract No. F19628-76-C-0106. Special appreciation is given to the Contract Monitor, Dr. G. Kenneth Yates, who participated directly in much of the work reported.

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1. INTRODUCTION

The primary objective of the work reported here was a determination of the adequacy of the simple square root relationship

$$A = K(E_t)\mathscr{F}(E_t)^{1/2} \tag{1.1}$$

between riometer absorption A and solar proton event flux $\mathscr{F}(E_t)$ as measured by the OV5-6 satellite. Here E_t is the integral flux energy threshold, and $K(E_t)$ is a constant that depends on E_t but is, to a good approximation, independent of the spectral parameters of the proton flux. A secondary objective was a determination of the optimum representation (rigidity, energy/nucleon, etc.) of the OV5-6 alpha/proton ratios. Work on this area was initiated earlier (Ref. 1.1), and most of the present effort was concentrated on the primary objective. It is our belief that the additional data which will become available (S3, SOLRAD satellites) in the near future should be utilized along with the available OV5-6 data to carry out a more detailed study of this area.

Results of the absorption-proton flux investigation are contained in the Appendix, and are considered to be essentially successful. This study used much of the data previously investigated, but considered in much more detail the atmospheric chemistry effects that cause the relation (1.1) to be a good approximation for night as well as day conditions. As discussed there, the diurnal variation between night and daytime absorption appears to be due to the rapid disappearance of atomic oxygen below about 75 km at night. Following removal of solar illumination, the lifetime of atomic oxygen is only a few seconds in the 50 km region, but it increases rapidly with altitude and has a lifetime of hours in the 90-100 km region. The effect of this is that the region of the atmosphere in which absorption peaks, about 50-60 km during the daytime, shifts upward as the solar zenith angle increases and reaches about 80 km under steady state darkness.

At night the energy threshold for (1.1) is about 2 MeV, consistent with the location of the absorption peak near 80 km. During the daytime the downward shift in the absorption peak altitude causes an upward shift in the energy threshold, to the vicinity of 5 MeV.

It appears likely that knowledge of the atomic oxygen decay times, and solar flux (the source of atomic oxygen) transmission through the atmosphere, could be combined with that gained by application of the simple relationship (1.1) to derive a relationship applicable to the dawn/dusk and dusk/dawn transition regions. This could involve, for example, either of two approaches: (1) an expression equivalent to (1.1) but with both K and E_t dependent upon solar zenith angle (calculable from geographic location and universal time), and, possibly, the time constants for atomic oxygen disappearance, or (2) a linear combination of the day and night relationships with two coefficients dependent upon solar zenith angle and atomic oxygen time constant. The first appraoch is probably more readily interpreted in physical terms (variation of E_t is associated with movement of the absorption peak between low and high altitudes); the second could be easier to implement on a computer-based program because of the two fixed energy thresholds.

2. CONCLUSIONS AND RECOMMENDATIONS

The approximate relationships between riometer absorption and solar proton flux has been demonstrated to be applicable for night as well as day conditions. The atmospheric chemistry underlying the difference in the two relationships is well understood.

It is recommended that the available OV5-6 data should be combined with any that becomes available from the S3 and SOLRAD satellites to investigate both the dawn/dusk, dusk/dawn transition periods and the optimum representation of alpha/proton ratios.

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APPENDIX

THE NIGHT AND DAY RELATIONSHIPS BETWEEN POLAR CAP RIOMETER ABSORPTION AND SOLAR PROTONS

ABSTRACT

The relationship between riometer-measured absorption of 30 MHz cosmic radio waves at Thule, Greenland and the extramagnetospheric 1-100 MeV solar proton event fluxes observed by satellite OV5-6 during 1969-72 is studied, with night and day conditions at Thule being separated. In the 70-90 km region in which most nighttime absorption occurs, ionization conditions are, in fact, relatively simple. This leads to a nighttime relationship between absorption and the square root of the integral proton flux, which is similar to that for daytime conditions. Based on previously measured effective recombination coefficients, theoretically optimum energy thresholds are determined for use in this approximate relationship. The values are 2.2 MeV and 5.2 MeV for night and day conditions, respectively. Both the approximate absorption, and that calculated by a reformulation of the standard approach, compare satisfactorily with extensive riometer measurements at Thule. The approximate relationships are employed in a real-time system that uses satellite proton data for prediction of radio wave (riometer) absorption.

INTRODUCTION

In a review of the ionospheric effects of solar activity, Reid [1972] observes that the most dramatic effect of a solar flare is known as polar-cap absorption (PCA) of radio waves. This phenomenon is due to intense atmospheric ionization produced in the D region by 1-100 MeV protons. As a result of the relatively low energy of these particles (compared, say, to cosmic rays) the configuration of the earth's magnetic field only allows access to the atmosphere in the polar regions. Thus, the strong absorption produced by this ionization is termed "polar blackout." Due to the distribution of transit times of the particles in reaching the earth, the absorption effects of a single flare reach a maximum hours after the flare and can last for several days or more. Hence, the consequences for radio communications and radar operations can be extreme with regard to both magnitude and duration.

Following the fundamental investigation of these PCA effects by Bailey [1959] for the 23 Feb. 1956 solar proton event (SPE) much theoretical and experimental work has been carried out. One of the instruments used is the riometer (relative ionospheric opacity meter), which records the total absorption of cosmic radio waves, as measured by a 5-50 MHz receiver directed near the zenith, and thus provides a measure of the blackout effect.

Information regarding the altitude dependence of the electron distribution that causes the absorption can be obtained by use of a multi-frequency riometer [Lavergnat and Berthelier, 1973], but most riometers are operated at a fixed frequency near 30 MHz. Hence, such a continuous recording throughout a given SPE forms the data generally available for investigative purposes. Some attention has been directed toward determination of the extent to which these data can be used to provide information on the incident proton spectrum [Reid, 1965, p227; Fichtel et al., 1963; Van Allen et al., 1964]. The continuous availability of satellite-measured proton spectra has also lead to development of techniques for theoretical calculation of the expected absorption by making assumptions regarding the important atmospheric ions and their reaction rates [for example, Bailey, 1959; Potemra et al., 1969; Stroscio and Sellers, 1975]. Such techniques can be difficult to apply, however, particularly in near real-time, and a simpler connection between proton fluxes and predicted absorption is desirable.

It can be argued that during the daytime when PCA event ionization conditions exist, the dependence of electron density n_e on ionization rate q is relatively simple, and absorption A dB should be proportional to the square root of the proton intensity [Fichtel et al., 1963; Bailey, 1964, p 531; Van Allen et al., 1964]. The relationship has often been expressed as

$$H(E_t, S) = J(E_t, S)/A^2 \tag{1}$$

where S represents all proton energy and angular spectrum parameters, and $J(E_t, S)(cm^2\text{-}sec)^{-1}$ is the omnidirectional integral flux above a chosen threshold energy E_t MeV. Solution of (1) for A yields the result of interest here,

$$A = m(E_t, S)J(E_t, S)^{1/2} \tag{2}$$

where $m(E_t, S) = H(E_t, S)^{-1/2}$. This equation would be most useful for absorption estimates if m were independent of S, thus requiring only the measured value of $J(E_t)$. Van Allen et al. [1964] found, however, that for the Explorer 7 proton data used, with E_t = 30 MeV, H varied greatly from SPE to SPE, implying a strong dependence on S for that E_t. Many other studies have been made of $H(E_t, S)$, mostly for daytime conditions, as summarized by Potemra [1972]. It has been found that there are values of E_t less than 30 MeV for which H varies much less with S, thus allowing a good approximation of A from (2) by use of an S-independent value of m. In a theoretical study, Potemra [1972] found E_t = 7 MeV as optimum, with m = 0.083 dB - $(cm^2\text{-}sec)^{1/2}$, and the relationship (2) was tested with good results for a series of SPE's in 1966-67. It was pointed out that due to the relative scarcity of nighttime absorption measurements, and the more complicated ionization conditions that exist then, tests of the relationship (2) for night are rare. Hence such a study was not made.

Earlier Reid [1969, 1970] had investigated the correlation of absorption with E_t for both day and night, although values of $m(E_t)$ were not derived. In one of these studies [Reid, 1970], a general survey of polar cap absorption (PCA) event problems, it was concluded ". . . that during the night the riometer is apparently more sensitive to protons with energies between 3 and 10 MeV than to the fluxes above 20 MeV that cause the bulk of the daytime absorption." The other study was associated specifically with the 2 Sept. 1966 SPE [Reid, 1969], where the conclusion was "These results demonstrate that daytime PCA measurements appear to give a good indication of time variations in the flux of protons with energy greater than about 5 MeV, whereas nighttime measurements tend to emphasize variations in the flux at somewhat lower energies, in the neighborhood of 3 MeV." Based on these two studies it is expected that the important energy region for nighttime absorption is approximately 3-5 MeV, whereas for daytime it is 5-20 MeV. Hence, daytime absorption is produced in a relatively low region of the ionosphere, while nighttime absorption is due to a higher altitude region: that ionized chiefly by 3-5 MeV protons. At vertical incidence these latter protons penetrate only to the 70-80 km region.

Throughout most of the PCA event nighttime D region, the dependence of n_e on q is, in fact, complex. In the upper portion of this region ($\gtrsim$75 km), however, where most nighttime absorption is produced, the dependence is simple and similar to that during daytime. Additionally, subsequent to the above work, results of an extensive series of riometer observations at Thule, Greenland, have become available [Cormier, 1973]. These cover SPE's during 1962-72 and include many nighttime periods.

Thus, we have carried out a theoretical investigation to determine the optimum threshold energy E_t for night conditions, in a manner similar to the daytime study made by Potemra [1972]. A summary of D region ion chemistry effects on riometer absorption and the formulation for the calculation are given first. The optimum theoretical value of E_t is then determined for nighttime at Thule and, for purposes of comparison with previous work, for daytime. Next, absorption is calculated by use of OV5-6 satellite-measured proton spectra both from the approximate square-root relationship and from the standard approach that takes into account the spectral shape. Finally, both of these absorption calculations are compared with measured results at Thule for a series of SPE's in the 1969-72 period, and applications of the approximate relationship are discussed; in fact, this relationship has (for the first time) provided a basis for real-time prediction of SPE induced radio wave attenuation in the nighttime polar ionosphere.

ION CHEMISTRY EFFECTS

Under steady-state conditions the usual continuity equations for the disturbed ionosphere [LeLevier and Branscomb, 1968] can be solved to yield [Potemra et al. 1969] the altitude profile of electron density that determines the amount of radio wave absorption,

$$n_e(z) = [q(z)/\Psi(z)]^{1/2} \tag{3}$$

Here $q(z)\,cm^{-3}\text{-}sec^{-1}$ is the ionization rate, and $\Psi(z)\,cm^{3}\text{-}sec^{-1}$ is the effective recombination coefficient,

$$\Psi = (1+\lambda)(B+E\lambda) \tag{4}$$

$$\text{where } \lambda = \frac{n_-}{n_e} = \frac{A_e}{D+En_+} \tag{5}$$

n_- and n_+ are the negative and positive ion concentrations, respectively; A_e is the rate of attachment of electrons to neutrals to form negative ions; B is the electron-positive ion recombination coefficient; D is the effective rate of detachment of electrons from all negative ions; and E is the negative ion-positive ion recombination coefficient. These coefficients are expected to represent numerous reactions in an average manner, but the values used are chosen based on a knowledge of the various ionic species present. Potemra et al. [1969] provide a tabulation of the values used in their model. Generally, the important positive ions are O_2^+ and NO^+, while in the upper D region ($\gtrsim$75 km) of primary interest here, the negative ions are O_2^- and possibly O^- [Narcisi, 1972].

As shown by (5), in general λ depends on n_+ and hence on q. In this situation Ψ then depends on q, and n_e from (3) is not simply proportional to $q^{1/2}$.

During the daytime, however, throughout the D region $En_+ \ll D$ [Potemra et al., 1969], and Ψ depends only on z.

A particularly important detachment mechanism is

$$O_2^- + O \rightarrow O_3 + e \tag{6}$$

During the daytime O concentrations are consistently high ($\gtrsim 10^{10}\,cm^{-3}$) throughout the D region and this reaction is very strong [LeLevier and Branscomb, 1968; Reid, 1969]. At night, however, the O concentration decreases very sharply below about 75 km, while above that altitude it is similar to its day level [Hunt, 1966; Swider et al., 1971; see also profiles in Narcisi, 1972]. This then introduces a diurnal variation in electron density below 75 km that is believed to be responsible for the observed diurnal variation in absorption [LeLevier and Branscomb, 1968; Reid, 1969, 1970]. It is important to note, however, that above 75 km this detachment mechanism is still operative at night, and here $En_+ \ll D$ as in daytime conditions [Stroscio and Sellers, 1974]. Thus, in the altitude region in which most nighttime absorption is produced, the ionization conditions are relatively simple, and the steady-state relationship (3) with q-independent Ψ is expected to be applicable, as it is for daytime conditions. In the following calculations, then, rather than making use of theoretical Ψ values as found from (4), we may employ the empirical results of Sellers and Stroscio [1975] for the 2-3 Nov. 1969 SPE. There q(z), as calculated from measured proton spectra, and $n_e(z)$ were combined to yield $\Psi(z)$ directly from (3) for both day and night conditions.

RIOMETER ABSORPTION FORMULATION

For present purposes the riometer absorption formulation of Potemra [1972] and Potemra and Lanzerotti [1971] has been rewritten by use of the steady-state relation (3) [Stroscio and Sellers, 1975] to exhibit explicitly the dependence of absorption A dB on the ionization rate altitude profile, $q(z)$:

$$A = \int b(z,f)\, q(z)^{1/2}\, dz \tag{7}$$

where

$$b(z,f) = k(f)\, \eta(z,f) \text{ (dB/cm)-(cm}^3\text{-sec)}^{1/2} \tag{8}$$

For the radio wave frequency f of interest here (30 MHz) the electron angular gyrofrequency $\omega_H << \omega = 2\pi f$, and

$$k(f) = 1.16/\omega^2 \text{ dB-cm}^2\text{-sec} \tag{9}$$

$\eta(z,f)$ is the atmospheric response function for any source of ionization that produces the profile $q(z)$:

$$\eta(z,f) = (\nu_m/\Psi^{1/2})\, U(\omega/\nu_m) \text{ cm}^{-3/2}\text{-sec}^{-1/2} \tag{10}$$

where $\nu_m(z)$ is the mean collision frequency, which is assumed to depend on the pressure $P(z)$ mb as given by Thrane [1968]

$$\nu_m(z) = 8 \times 10^7\, P(z) \text{ sec}^{-1} \tag{11}$$

The function $U(x)$ is written in terms of the $C_{5/2}(x)$ integral tabulated by Dingle et al. [1957]:

$$U(x) = x^2\, C_{5/2}(x) \tag{12}$$

$U(x)$ is defined in such a way that when $x = \omega/\nu_m \longrightarrow \infty$, $U(x) \longrightarrow 1$, $\eta(z,f) \longrightarrow \nu_m/\Psi^{1/2}$, and hence is independent of f, and (7) becomes the Little and Leinbach [1958] expression that results from the assumption of energy-independent collision frequency. Expressing f in MHz and z in km yields

$$b(z,f) = 2.94 \times 10^{-9}\, \eta(z,f)/f(\text{MHz})^2 \text{ (dB/km) - (cm}^3\text{-sec)}^{1/2} \tag{13}$$

The other quantity required in (7) is the q(z) profile produced by the SPE protons, which is calculated by the method of Sellers and Hanser [1973]. Details of application to the present problem are given in Stroscio and Sellers [1975]; here we summarize only the final equations used. The proton differential spectrum in energy E and pitch angle α, $j(E,\alpha)(\mathrm{cm}^2\text{-sec-sr-MeV})^{-1}$, is of the form

$$j(E,\alpha)dEd\Omega = \mathcal{F} k \cos^{\beta}\alpha\, E^{-n}\, dEd\Omega \tag{14}$$

Here k is a constant that normalizes $j(E,\alpha)$ such that $\mathcal{F}(\mathrm{cm}^2\text{-sec})^{-1}$ is the number of particles per second with energy between E_1 and E_2 that cross a plane perpendicular to $\alpha = 0^{\circ}$. For the isotropic ($\beta = 0$) angular distribution used here it can be shown [Sellers and Kelley, 1975] that in the altitude region of interest q(z) can be calculated accurately under the assumption that the range R for protons of energy E MeV is given by

$$R = (a/A_o)E^{1/a}\ \mathrm{g/cm}^2 \tag{15}$$

where

$$a = 1/1.775 = .5634 \tag{16}$$

and

$$A_o = 231.8\ \mathrm{MeV}^{1/a}\text{-}\mathrm{cm}^2/\mathrm{g} \tag{17}$$

Then

$$q(z,n,\beta) = (\mathcal{F}k)\, J(n,\beta) \left(\frac{d(z)}{H_e(z)}\right)^{-a(n-2)} \left[\frac{D(X_2,n,\beta)}{D(0,n,\beta)} - \frac{D(X_1,n,\beta)}{D(0,n,\beta)}\right] \tag{18}$$

Here $H_e(z)$ is the slowly-varying scale height that would exist at z if the atmosphere were, in fact, exactly exponential at that point

$$H_e(z) = d(z)/\rho(z)\ \mathrm{cm} \tag{19}$$

where d(z) $\mathrm{g/cm}^2$ and $\rho(z)$ $\mathrm{g/cm}^3$ are the atmospheric depth and density, respectively, and

$$X_1 = d(z)/R_1 \ , \ X_2 = d(z)/R_2 \tag{20}$$

where R_1 and R_2 are the ranges for the energies E_1 and E_2 between which the spectrum parameter is n.

$$D(x, n, \beta) = \begin{cases} \displaystyle\int_x^1 X^{a(n-2)-1} F(X, \beta)\, dX & x < 1 \\ = 0 & x \geq 1 \end{cases} \tag{21}$$

where, for an isotropic angular distribution

$$\left.\begin{aligned} F(X, 0) &= F_o X^r (1 - X)^w \\ F_o &= 1.8680 \\ r &= 1.1749 \\ w &= 0.5358 \end{aligned}\right\} \tag{22}$$

and

$$J(n, 0) = [\pi a\, D(0, n, 0)/Q]\, (a/A_o)^{a(n-2)} \tag{23}$$

where $Q = 36 \times 10^{-6}$ MeV is the energy to produce one ion-electron pair in air, and D(0, n, 0) can be calculated from a closed form [Stroscio and Sellers, 1975].

In the following section the optimum threshold energy E_t is determined by use of A as calculated from (7). Since our spectrum (14) is expressed in terms of the flux $\mathcal{F}$, rather than the omnidirectional flux J, we define the quantity

$$K(E_t, n) = A/\mathcal{F}(E_t)^{1/2} \text{dB-(cm}^2\text{-sec)}^{1/2} \tag{24}$$

Here, $\mathcal{F}(E_t)$ is the number of particles per second with energy greater than E_t that cross a plane perpendicular to the direction $\alpha = 0^o$. The relationship between K and m, Eq. (2), for an isotropic angular distribution is

$$m = K/\sqrt{2} \tag{25}$$

Calculation of riometer absorption from (7) for use in (24) thus employs $b(z,f)$ from (13) and $q(z,n,\beta)$ from (18). The z integration in (7) is carried out from a low altitude $z_1 = 30$ km to an upper altitude $z_2 = 100$ km. Although $D(x,n,\beta)$ in (21) can be expressed in terms of the incomplete beta function, for $x \neq 0$ it is necessary in general to perform this integration numerically to determine $q(z)$ for each z of interest. For determination of the optimum threshold energy, however, it is assumed that the power-law in energy extends to ∞ at high energy, so that $X_2 = 0$, and to sufficiently low energy that the absorption contribution is negligible for particles having energy lower than the .5 MeV necessary to reach the altitude z_2. As a consequence, it is not necessary to specify an actual lower limit E_1, and $X_1 \geq 1$ for all $z \leq 100$ km. Hence, the first term in the bracket in (18) is unity, the second is zero, and the z-dependence of q is dominated by the n-dependent power-law in $d(z)$.

The scale height $H_e(z)$ and atmospheric depth $d(z)$ are tabulated by Stroscio and Sellers [1974] at 5 km intervals from 30 to 100 km for 60°N and 90°N and for each month of the year. Corresponding values of $\eta(z,f)$ are also given for both day and night, as derived from $\psi(z)$ data for the 2-3 Nov. 1969 SPE under the assumption that ψ depends only on atmospheric density $\rho(z)$ [Sellers and Stroscio, 1975]. Figure 1 shows $b(z,f)$ as calculated from (13) for the 60° N and 90° N (appropriate for Thule) January models. Each is very close to the yearly average for that latitude, and all calculations using these profiles are considered to be suitable for use as annual averages. Examination of such $b(z,f)$ altitude profiles allows a direct determination of those altitude regions that are most efficient for production of absorption by any source of ionization. The relative maximum between 50 and 70 km for night results from determination of $\eta(z)$ from (10); it is not present in either the $\nu_m(z)$ or $\Psi(z)$ data. For SPE's this peak is of little significance, since normally $n \gtrsim 1.5$ in Eq. (14), and most of the nighttime absorption is produced by the numerous relatively low energy protons that stop in the 70-90 km altitude region where $b(z,f)$ has its maximum value. This dual peaked structure,

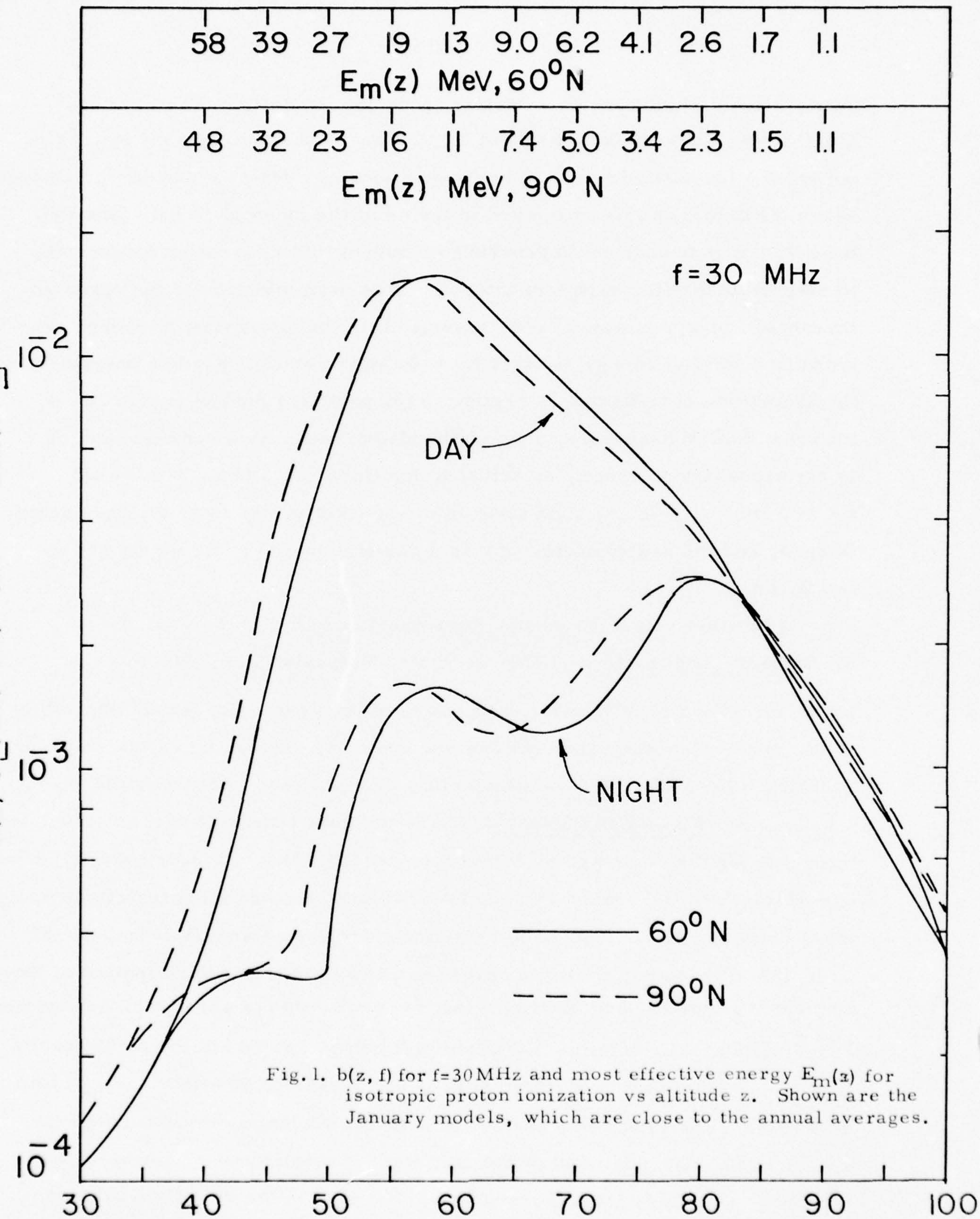

Fig. 1. b(z, f) for f=30MHz and most effective energy $E_m(z)$ for isotropic proton ionization vs altitude z. Shown are the January models, which are close to the annual averages.

obtained here by use of empirical $\Psi(z)$ results for the $n_e(z)$ determination, confirms a very similar structure obtained by LeLevier and Branscomb [1968, Fig. 14] by use of rate constants in the full continuity equations for determination of $n_e(z)$. In that case the q(z) profile produced by the nuclear detonation under investigation caused most of the absorption to be produced in the vicinity of the lower altitude peak.

For protons of range R(E) the ionization rate per unit of isotropic flux at $X = d(z)/R$ is proportional to the function $F(X, 0)$ of (22). These protons produce maximum ionization where $F(X, 0)$ is maximum - at $X = X_m = .69$. Since heavy particles ionize most heavily very near the end of their range, for such a monoenergetic isotropic spectrum we can define a most effective energy $E_m(z)$ for an altitude z as that for which the range is $R_m(z) = d(z)/.69$. $E_m(z)$, found from (15), is shown at the top of Figure 1. From this figure it is clear that the approximate energy range of primary importance for absorption production at night is 1-5 MeV, while during the day it is 5-25 MeV. This nighttime range extends to somewhat lower energy than would be expected based on the Reid [1969] study, while the daytime range is consistent with that study. For power-law energy spectra, Potemra [1972] found daytime polar-cap absorption to be affected most by 15 MeV protons. This is almost exactly the energy expected based on the peaks in b(z, f) in Figure 1.

OPTIMUM THRESHOLD ENERGY DETERMINATION

Figures 2 and 3 show 90°N day and night results computed from Equation (24) by the procedures described above [Stroscio and Sellers, 1975]. As shown in Table 1*, the computed optimum daytime threshold energy is approximately 5.2 MeV. Interestingly, an energy region in which $K(E_t, n)$ varies little with n also occurs for nighttime. But in this case it is at a lower energy, approximately 2.2 MeV, as would be expected from the b(z, f) dependence in Figure 1. An identical computation for 60°N yields insignificantly different results (± .1 MeV) for E_t, as expected from the small

*See page 28

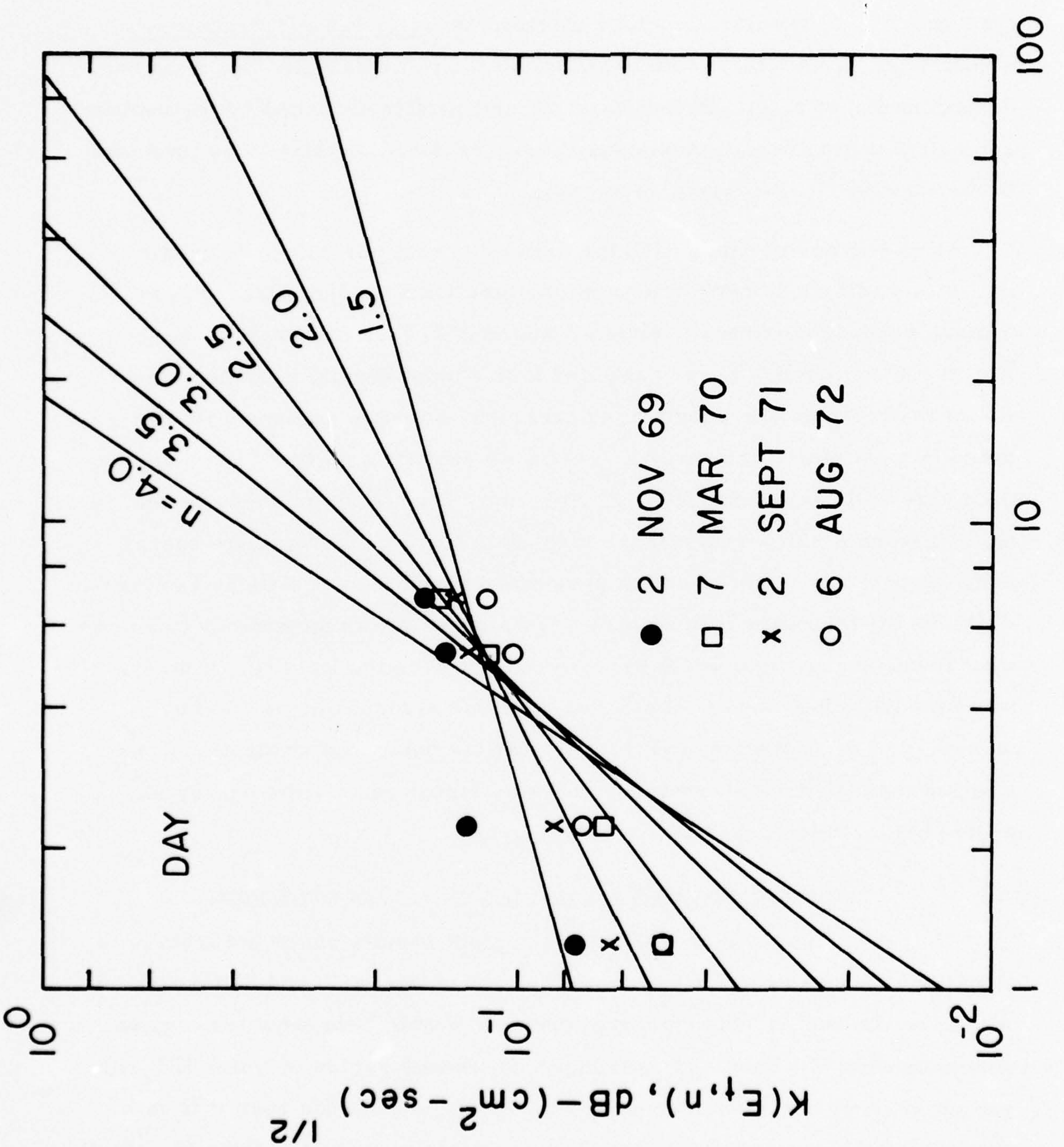

Fig. 2. Day values of $K(E_t, n)$ computed for power-law energy spectra and determined empirically from Thule, Greenland 30 MHz riometer absorption and OV5-6 satellite proton fluxes.

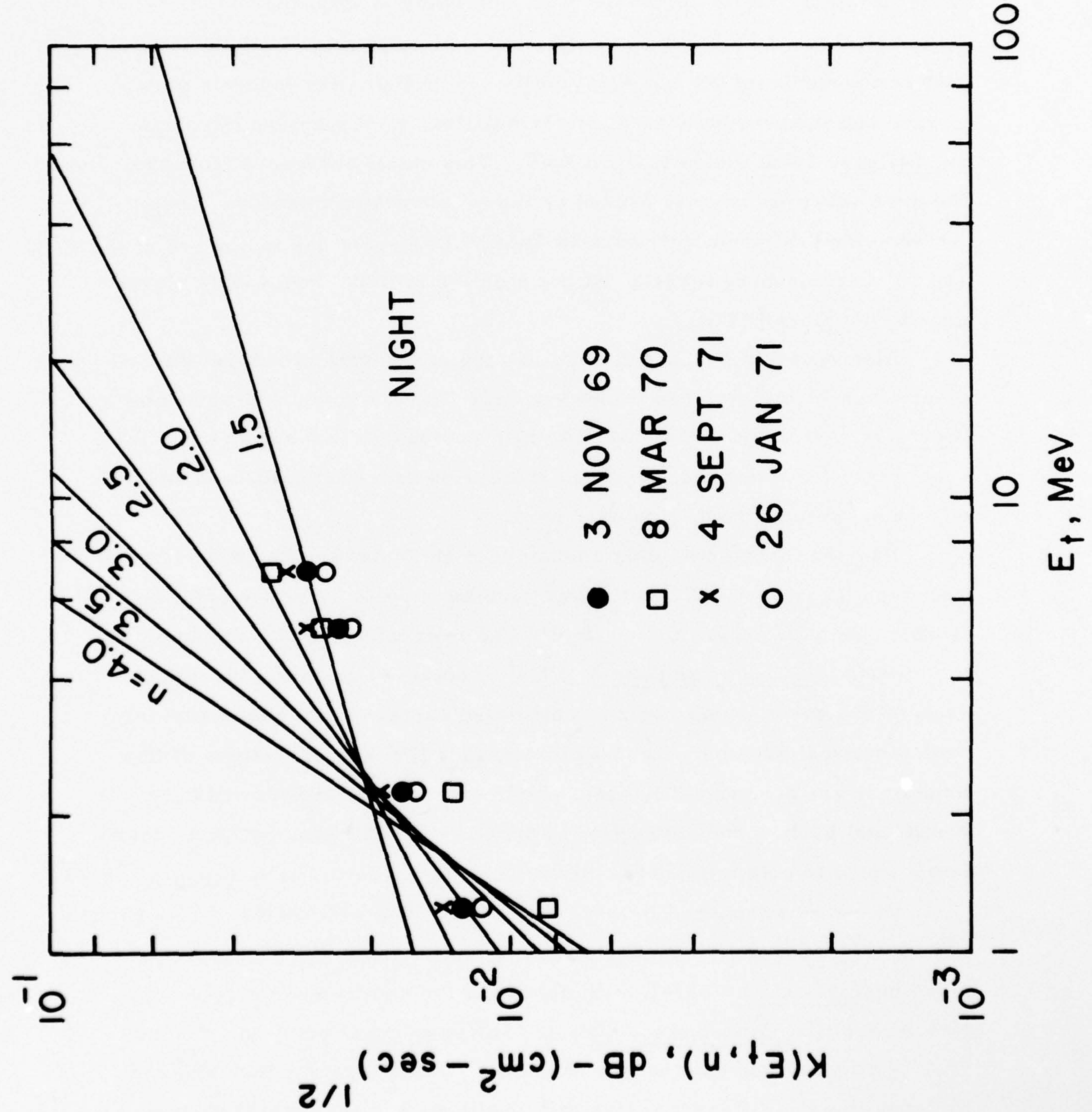

Fig. 3. Night values of $K(E_t n)$ computed for power-law energy spectra and determined empirically from Thule, Greenland 30 MHz riometer absorption and OV5-6 satellite proton fluxes.

b(z,f) latitude-dependent deviations in Figure 1. The day value 0.081 for m is to be compared with the value 0.083 for E_t = 7 MeV found by Potemra [1972] by use of an average latitude-independent atmospheric model and $\Psi(z)$ profile. With those atmospheric parameters and the present absorption formulation, a comparison [Stroscio and Sellers, 1975] yields $E_t \approx 6.5$ MeV. This small difference from the Potemra value probably is caused by the q-calculation methods. Thus the somewhat different day value in Table 1 is largely due to our use of the 90°N and 60°N atmosphere models, rather than the latitude-independent model used by Potemra [1972].

Also shown in Figures 2 and 3 are typical empirical values of K determined from (24) by use of the available 1969-72 coincident absorption [Cormier, 1973] and OV5-6 satellite SPE proton flux measurements. All such SPE's for which the maximum absorption exceeded 2 dB, and several of less magnitude, have been used here.

The zenith-directed riometer antenna at Thule is of the two-element Yagi type [Cormier, 1973] with characteristics given by Edson and Goldman [1963]. We have approximated the FWHM beam width as 50° and employed the method of Sellers and Hanser [1974] to obtain ~1.15 as the maximum ratio of measured broad-beam to calculated narrow-beam absorption for such a vertical antenna. As observed by Holt [1973], corrections of this magnitude are not normally made, and that procedure is followed here. A seasonal background correction as large as 0.8 dB was, however, taken into account to obtain the broad-beam absorptions reported by Cormier [1973].

OV5-6 was launched in May, 1969 with a 30.6° inclination, 2.9 R_E perigee and 19.3 R_E apogee. General features of the satellite and instrument are given by Yates et al. [1974], with details of the semiconductor telescope-type detector in Hanser et al. [1973]. The proton flux between 1 and 100 MeV is measured in nine energy channels. These data are then utilized to determine the differential flux that would exist at the central energy points in each channel, and a point-to-point fit of type (14) is made to determine the complete energy spectrum [Hanser et al., 1973]. Integral fluxes above the thresholds E_t can then be calculated as was done for the points in Figures 2 and 3. Propagation effects between the extramagnetospheric OV5-6 location and the polar ionosphere have not been taken into account. These may be important at times, although the use of Thule ($\sim 88^{\circ}$N geomagnetic) riometer data does eliminate the problem of geomagnetic cutoff, which is insignificant at that latitude.

For all events used except that of March, 1970, the event-averaged power-law exponent was between 1.5 and 2; for the March SPE it was 3.3 [Stroscio et al., 1976]. Unfortunately, this latter event was relatively small, and the empirical values of K, especially at night when the SPE-induced absorption was less than 1 dB, have less accuracy than those of the other events. This may be the reason that the deviation is largest for this event, although the other empirical night results also tend to be slightly low near the optimum value of E_t. Overall, however, the agreement between empirical and calculated results is reasonably good.

RIOMETER ABSORPTION COMPARISONS

From Equation (24) the approximate absorption is now given for either day or night by

$$A = K(E_t)\mathscr{F}(E_t)^{1/2} \tag{26}$$

where $K(E_t)$ and E_t are the appropriate values from Table 1, and $\mathscr{F}(E_t)$ is the integral flux calculated from the complete point-to-point energy spectrum fit determined from the OV5-6 measurements. Also, an "exact" absorption calculation can be made by applying (18) for the fit in each energy channel and summing the contributions from all channels to obtain the total $q(z)$ for use in (7) [Stroscio and Sellers, 1975]. Figures 4-8 show the comparison of these two calculations with the measured Thule absorption [Cormier, 1973] throughout the five SPE's used here. Three of these events are for combined day/night conditions, one (August, 1972) for all day conditions and the other

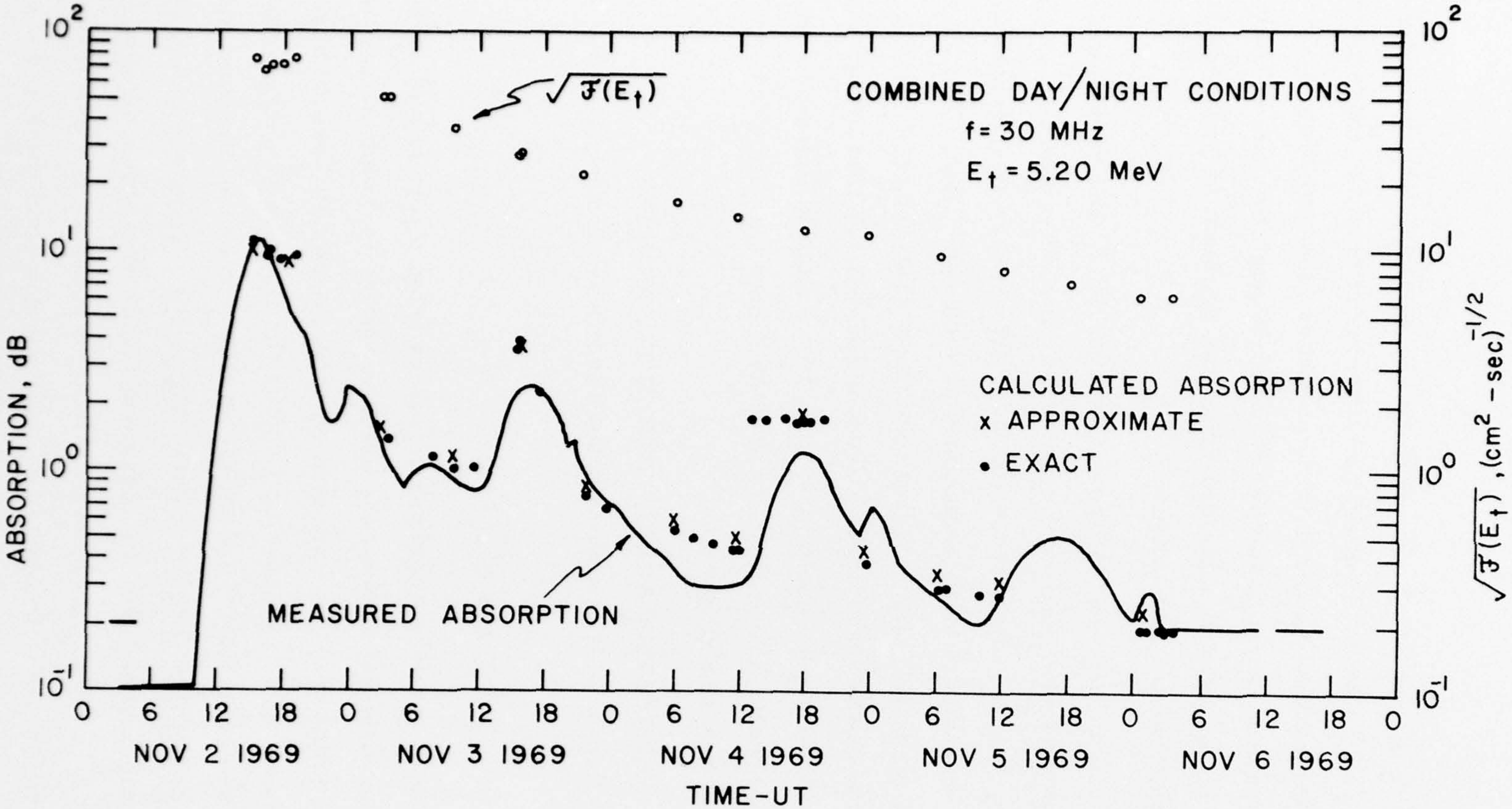

Fig. 4. Calculated and measured Thule riometer absorption for 2 November 1969 SPE.

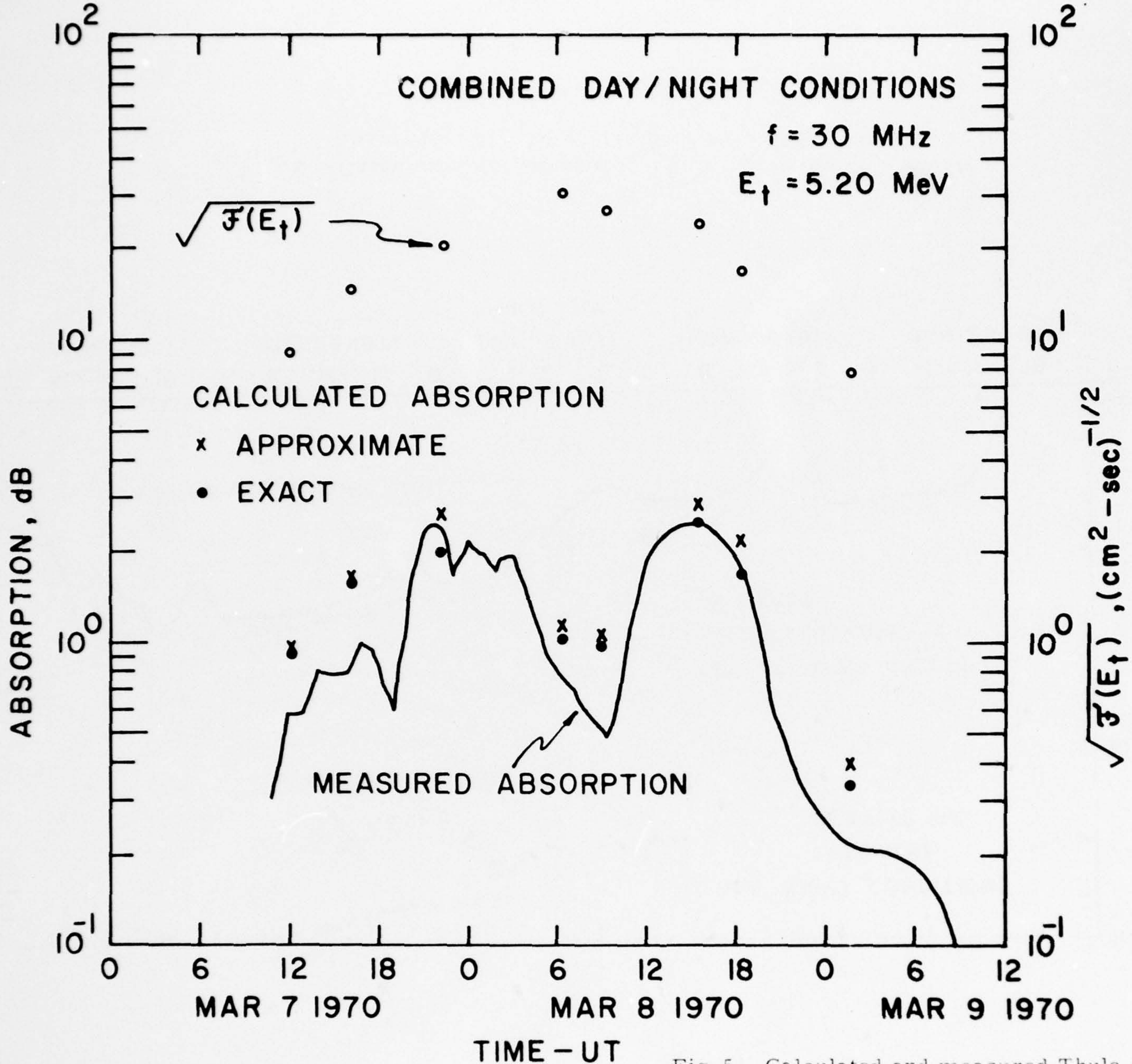

Fig. 5. Calculated and measured Thule riometer absorption for the 7 March 1970 SPE.

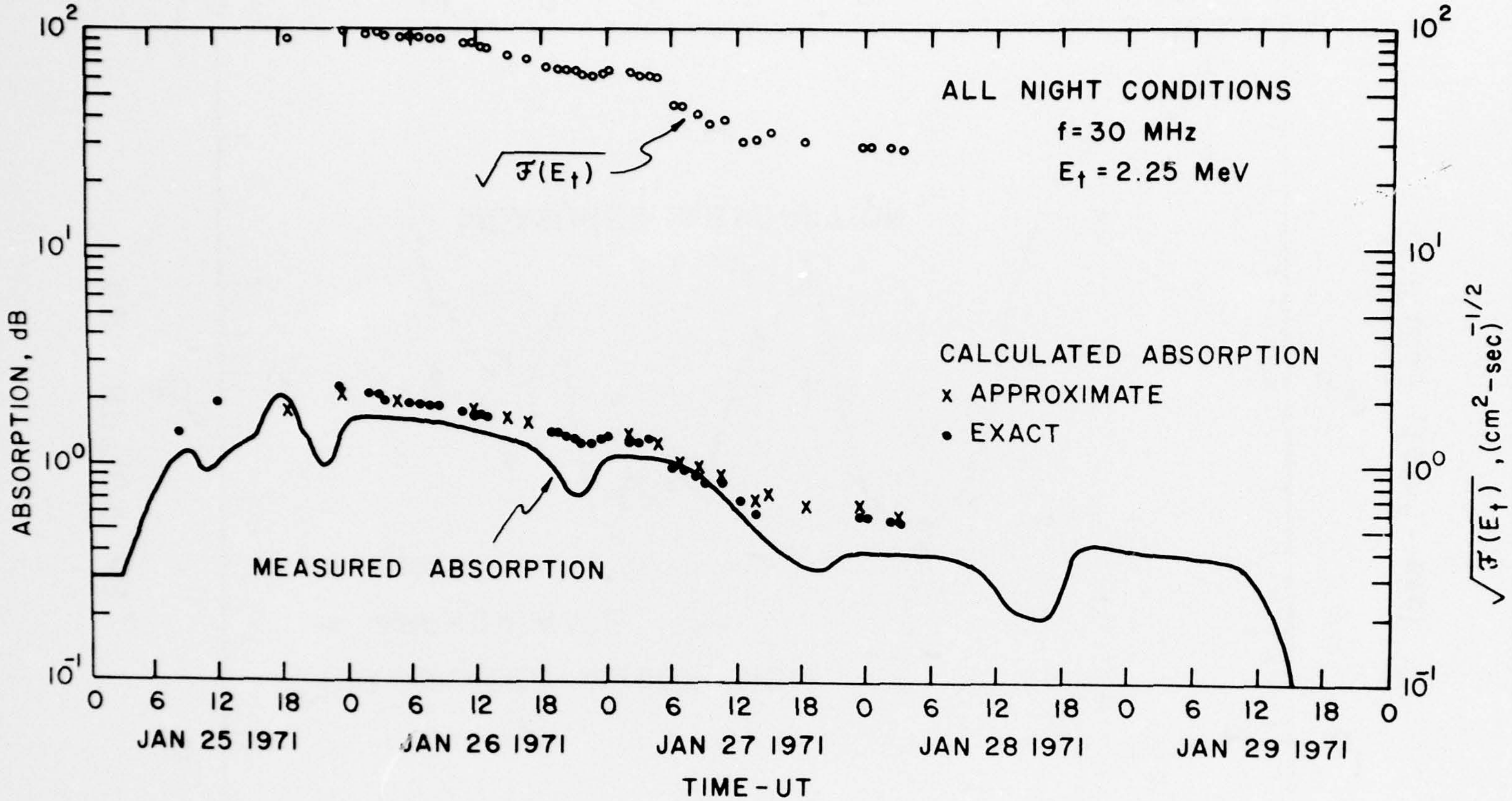

Fig. 6. Calculated and measured Thule riometer absorption for the 25 January 1971 SPE.

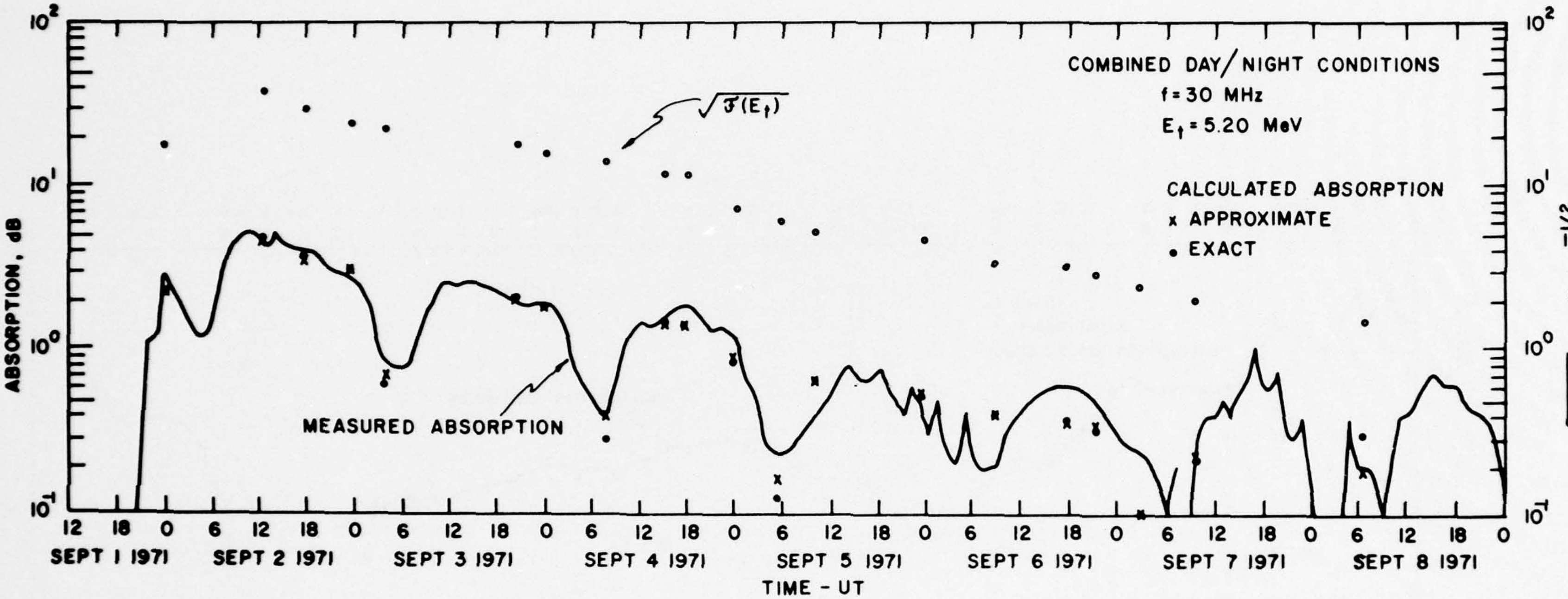

Fig. 7. Calculated and measured Thule riometer absorption for the 1 September 1971 SPE.

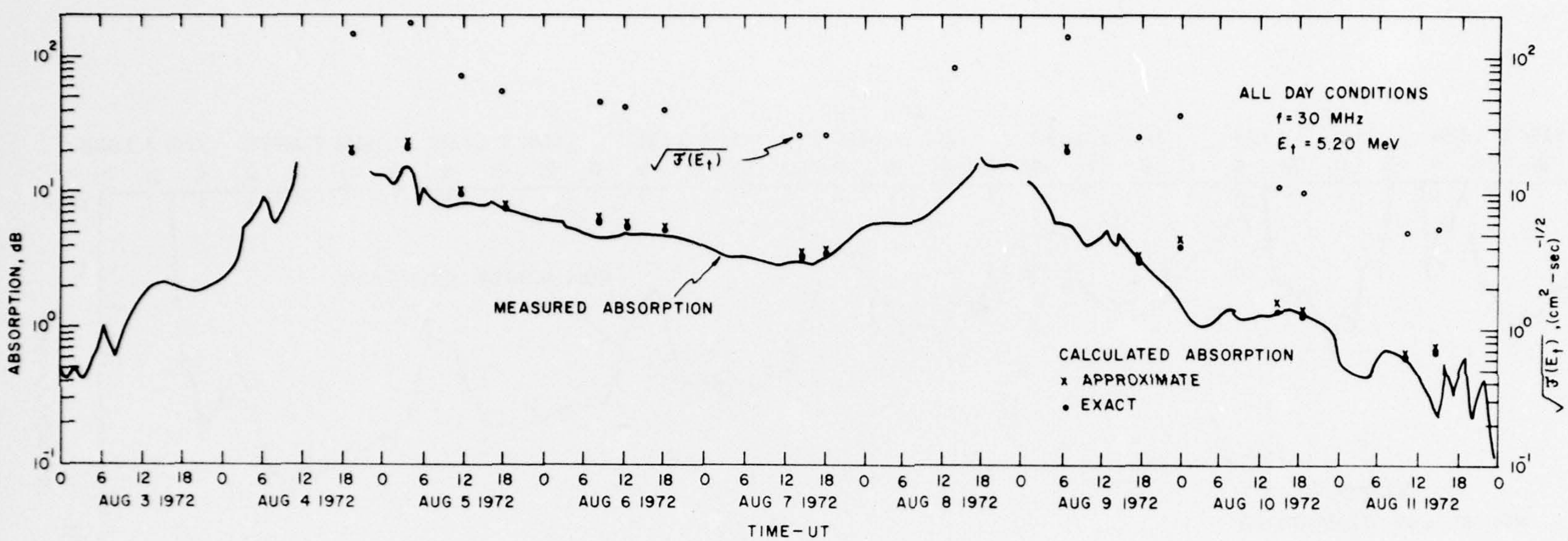

Fig. 8. Calculated and measured Thule riometer absorption for the 3 August 1972 SPE.

(January, 1971) for all night conditions. In this latter event the integral flux is shown for the nighttime optimum value of E_t. No estimates of measured absorption accuracy are shown, since these are not given by Cormier [1973].

In Figure 4 night conditions are present from 2000 UT to 1230 UT at Thule, and the diurnal variation in measured absorption is apparent. Absorptions calculated based on the extramagnetospheric OV5-6 proton fluxes agree reasonably well with the measurements in an average manner, although they are somewhat high during the Nov. 3 and 4 peaks.

However, the striking feature is the excellent agreement of the approximate and exact calculations for both day and night conditions. In our opinion, this agreement strongly supports the arguments above that both day and night estimates of absorption can be made by use of (26). Calculation for the day/night and night/day transition periods clearly requires a different approach, since the transitions are not abrupt and can last several hours.

Low values of absorption characterized most of the 7 March 1970 event shown in Figure 5, which also included both day and night conditions. The absorption values plotted between 0600 and 1200 UT on 8 March and the single value at 0200 UT on 9 March all represent night conditions.

The 25 January 1971 event of Figure 6 is an all night event at ground level. At higher altitudes the sun is present at about 1700 UT; however, it clearly is not present long enough to produce daytime atmospheric response conditions. The time dependence of the calculated absorption closely follows the measured results, although it is somewhat high onthe average.

Figure 7 depicts the 1 September 1971 event, which is similar to the 2 November 1969 event in that both day and night conditions were present for extended periods of time. Nighttime conditions exist between 0100 and 0800 UT. In contrast to the 2 November 1969 event, the calculated values of absorption for night conditions are slightly below the measured results, although the day values agree extremely well.

The last event studied here is that of 3 Aug. 1972, displayed in Figure 8. This event, one of the largest ever recorded, occurred in all daytime conditions at Thule. Although the calculated values are slightly high at some times, the generally good agreement is in accord with the fact that large PCA values tend to be independent of the narrow-beam approximation.

CONCLUSIONS

Based directly on the altitude region in which b(z, f) peaks, it has been shown that the proton energy range of primary importance for PCA is 5-25 MeV during the daytime and 1-5 MeV at night. This relatively low nighttime energy range provides the basis for a simple characterization of cosmic radio wave absorption under night conditions, similar to that applicable during daytime PCA.

For the events studied, reasonably good agreement was obtained, for both day and night, between the measured absorptions at Thule and those calculated from (7) based on the b(z, f) profiles of Figure 1 and the extramagnetospheric OV5-6 proton fluxes. Deviations, where they occur, generally tend to show too much calculated absorption, although instances in which the calculation is slightly low also occur (Fig. 7). Transport of the proton fluxes into the polar atmosphere from the OV5-6 location was not taken into account, and the day-night transition for the D region was taken to be abrupt. Further, the Thule absorptions were calculated by use of recombination coefficients based on those originally measured at Ft. Churchill. These are probably the major factors that serve to limit the agreement obtainable by use of the b(z, f) profiles given here.

The agreement between our "exact" and approximate calculations supports the use of the approximate relationship of Eq. (26) between absorption and solar proton fluxes for night as well as day conditions when the appropriate values of E_t and $K(E_t)$ are used. A technique has been developed (the Smart-Shea Prediction Method) that incorporates this relationship and is in use by both the N.O.A.A. and the A.F. for forecasting the effects of

SPE's [D. F. Smart, personal cummunication, 1977]. From available satellite proton data (SMS-GOES, Vela) the expected absorption is calculated and compared in real-time with measurements. Since the computation can also be made at night, it allows for the first time a continuous comparison of measured and calculated radio wave absorption, and a prediction of the severity of the blackout effect. Of course, at present only the steady-state day and night cases have been treated. The day/night transition periods (which can last several hours) require a different approach.

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Table 1. Parameters for Approximate Absorption Calculation at Thule

	E_t, MeV	$K(E_t)$, dB-$(cm^2\text{-sec})^{1/2}$	$m(E_t)$, dB-$(cm^2\text{-sec})^{1/2}$
Day	5.2	0.115	0.081
Night	2.2	0.020	0.014

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Final Report

THE RELATIONSHIP BETWEEN POLAR CAP RIOMETER ABSORPTION AND SOLAR PARTICLES

Bach Sellers
Frederick A. Hanser

Errata

Replace pages 26 and 30 with attached pages.

AIR FORCE GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
HANSCOM AFB, MASSACHUSETTS 01731

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For the events studied, reasonably good agreement was obtained, for both day and night, between the measured absorptions at Thule and those calculated from (7) based on the b(z,f) profiles of Figure 1 and the extramagnetospheric OV5-6 proton fluxes. Deviations, where they occur, generally tend to show too much calculated absorption, although instances in which the calculation is slightly low also occur (Fig. 7). Subsequent to the calculations in this paper it has been argued [Swider and Chidsey, 1977] that an earlier $\nu_m(z)$ result due to Thrane and Piggott [1966], which is 20% lower than that given by Eq. (11), might, in fact, be correct. If so, all of the absorptions calculated here, and the constants in Table 1, should be lowered by that amount. This would bring theory and experiment into better average agreement. Additional factors are as follows: transport of the proton fluxes into the polar atmosphere from the OV5-6 location was not taken into account, the day-night transition for the D region was taken to be abrupt, and the Thule absorptions were calculated by use of recombination coefficients based on those originally measured at Ft. Churchill. These are probably the major factors that serve to limit the agreement obtainable by use of the b(z,f) profiles given here.

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